

SIXTH INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES

Topic 2.2: Internal influences on Tropical Cyclone formation

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Abstract

This report summarizes work completed since ITWC-V that contributes to an improved understanding of the internal influences on tropical cyclone (TC) formation. The report argues the importance of low-level vorticity enhancement during TC genesis due to convergence in convective regions, both on the individual convective element scale and on the system scale. It is argued that large-scale processes essentially drive TC genesis. These large-scale processes set up a favorable environment, and initiate the mesoscale intensification mechanisms that construct the TC-scale vortex. It is argued that these large-scale processes, and a significant portion of the mesoscale processes, are represented in contemporary global NWP models. However, the finer detail not resolved by these models is believed to be important for a more complete understanding of intrinsic upscale growth mechanisms that can occur in rotating moist convective systems and the TC genesis process in particular. This has been the subject of much research in the past four years.

2.2.1. Introduction

In the four years since IWTC-V, TC formation has continued to be the least understood phase of the TC life cycle. Modelling studies have pushed rapidly forward our understanding of genesis in a variety of numerical models, and have provided plausible genesis theories to be tested. TC genesis is becoming better understood in numerical models, but we still have some way to go to discover how genesis operates in the real world. Recent observational studies are beginning to show that some aspects of the genesis process observed in numerical models do indeed operate in the real world, and provide some confidence that the models may be getting the right answers for the right reasons. In the past, lack of an observational network of sufficient spatial and temporal resolution over the open ocean has been the main reason for the lagging understanding of genesis. This is still an important issue. Doppler radars have recently provided some useful information of the finer scale details of the genesis process. There are still limitations, however, in that fixed radars are land based, and require genesis to occur near land within range of the radar (Sippel et al. 2006), and aircraft-based radar can get to the genesis area but cannot provide a continuous time record of observations (Reasor et al. 2005). Together, high-resolution, cloud-

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resolving modelling studies and the slowly improving observational network are beginning to reveal some of the mysteries of TC formation.

In section 2.2.2 of this report, a historical review of genesis theories that focuses on the internal dynamics of genesis is presented that contrasts the top-down versus bottom-up debate. It is suggested that a loose genesis definition was partly responsible for the disagreement between the proponents of each theory, and that the debate has been long-lived because insufficient observations have existed to prove or disprove either theory. In section 2.2.3 it is noted that inconsistent genesis definitions exist throughout the genesis literature, and it is proposed that genesis be recognised as a process consisting of two stages (e.g., Karyampudi and Pierce; 2002): (i) the sub-synoptic scale organisation of an environment favorable for genesis (genesis preconditioning); and (ii) the mesoscale focussing of the larger-scale environmental vorticity into a TC-scale vortex. In section 2.2.4 recent modelling results are presented. Higher resolution cloud-resolving models are shown to exhibit fine-scale vortex formation and interactions very similar to those in recent observational studies. Perhaps surprisingly, coarser resolution models with convective parameterization, which do not resolve such features, have been shown to have good success in genesis forecasting. In section 2.2.5 the implications of this result is explored and the suggestion is made that TC genesis might be largely driven by scales resolvable by these coarser resolution models.

2.2.2. Top-down versus bottom-up: The debate moves forward.

2.2.2.1 Theoretical ideas revisited

Two main groups, Liz Ritchie and colleagues and Michael Montgomery and colleagues have provided contrasting views of internal influences on TC genesis over the last 10 years or so. Both groups recognised the importance of Mesoscale Convective System (MCS) dynamics in driving the genesis process on the mesoscale level, and both established conceptual models of vortex enhancement leading to TC genesis.

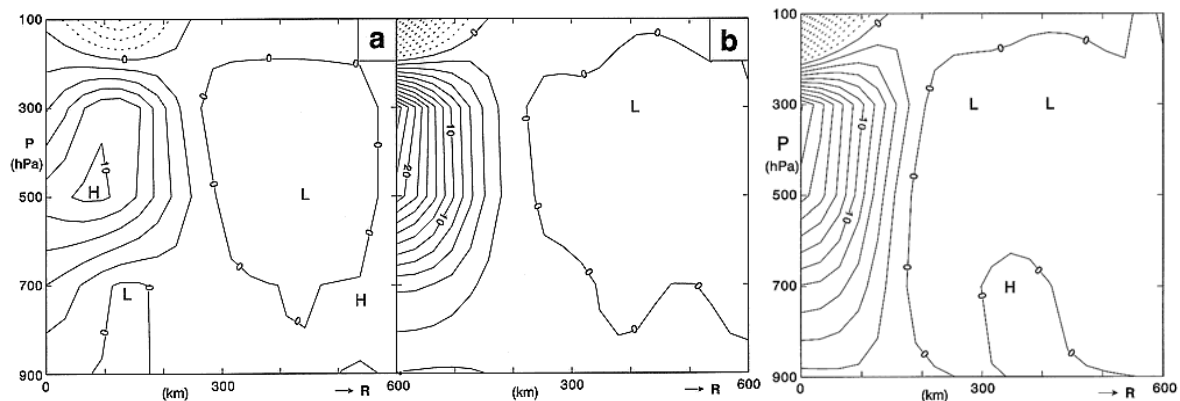


Figure 1: Radial average of vorticity for merger of midlevel vortices in a baroclinic model with no diabatic heating. In (a) time = 72 h and (b) time = 120 h there is no background vorticity. In (c) time = 120 hours, background vorticity equivalent to three times the planetary vorticity was included (contours: $2.0 \times 10^{-5} \text{ s}^{-1}$). Images taken from Fig. 12 and 13 of Ritchie and Holland (1997).

Ritchie and colleagues based their dynamical understanding of MCSs on the well-documented mid-latitude terrestrial MCS, and developed a vortex intensification theory based on vortex interactions of MCS vortices

(Ritchie and Holland 1997; Simpson et al. 1997). This theory was based on observations of MCS behavior in TC genesis environments that strongly resembled vortex interactions as represented in two-dimensional vorticity dynamics (Dritschel and Waugh 1992). They proposed that the MCS in a genesis environment consisted of a large stratiform precipitation region with an accompanying Mesoscale Convective Vortex (MCV), and that this mid-level vortex is responsible for the vortical behavior of the MCS cloud masses evident in visual and infrared satellite imagery. Ritchie and colleagues demonstrated with idealized models that merger of mid-level vortices in a cyclonic environment resulted in a more intense vortex with increased horizontal and vertical scale. This is illustrated in Fig. 1. They advocated a top-down hypothesis whereby a number of MCV interactions leads to a resulting vortex that eventually reaches the surface, kick-starting the hurricane heat engine. They also show that the vertical penetration is proportional to the background rotation (Fig. 1c).

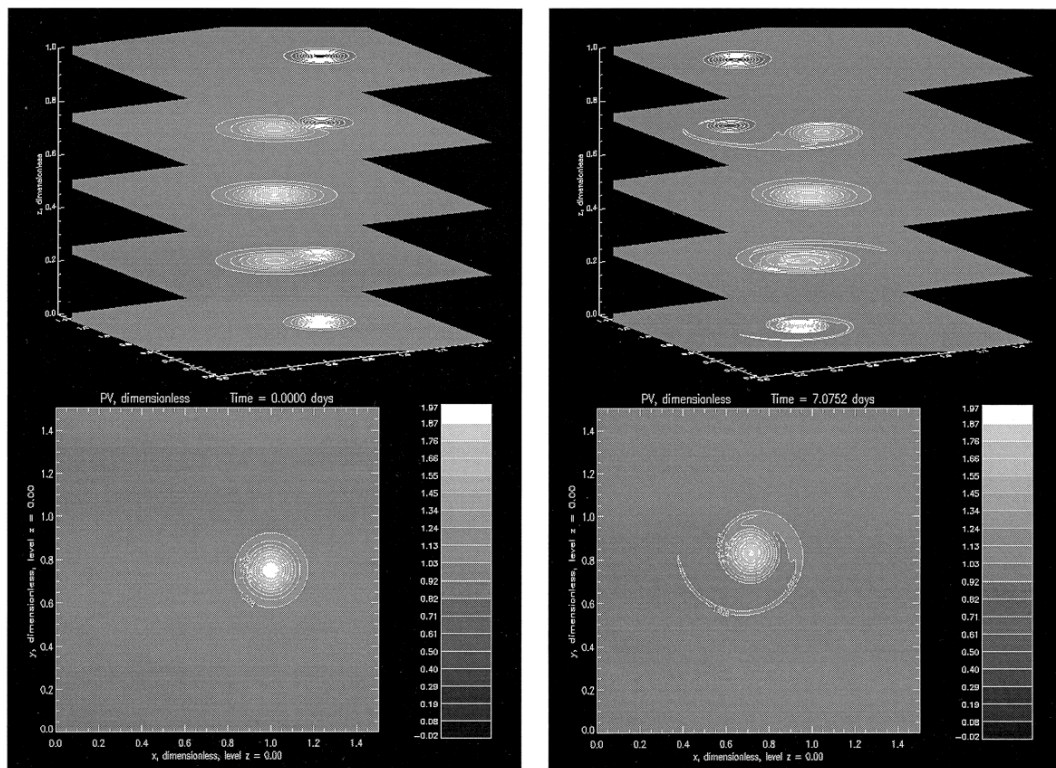


Figure 2: Contours of PV versus x and y on $z = 0$, $z = 0.25$, $z = 0.5$, $z = 0.75$, and $z = 1$, as well as a plan view of contours of PV versus x and y on $z = 0$ for the midlevel vortex with single-cluster convection at (a) time $t = 0$, and (b) $t = 7$ days. In (a) the MCV is evident in the domain center, and to the right there is a PV anomaly representing the effects of low-level convergence and upper-level divergence that might be expected to develop following an episode of deep cumulonimbus convection. In (b) the resulting vortex structure shows a near upright low- to mid-level cyclonic core with maximum intensity at low-levels. Images taken from Figs. 12 and 13 of Montgomery and Enagonio (1998).

Montgomery and colleagues based their conceptual model on observations of Zehr (1992) that low-level vortex intensification followed bursts of intense deep convection. They showed deep convective-like Potential Vorticity (PV) anomalies embedded in a MCV led to vortex interactions that resulted in a near-symmetric vortex with strong low-level vorticity

(Montgomery and Enagonio 1998; Enagonio and Montgomery 2001) on plausible development time-scales. This is evident in Fig. 2.

Another hypothesis in the top-down category is what we call the “shower-head” theory by Bister and Emanuel (1997). They suggested that sustained precipitation in the stratiform cloud deck would gradually saturate the relatively dry and cold layer below, from the top down while advecting cyclonic vorticity to the surface. A schematic summarizing their theory is presented in Fig. 3.

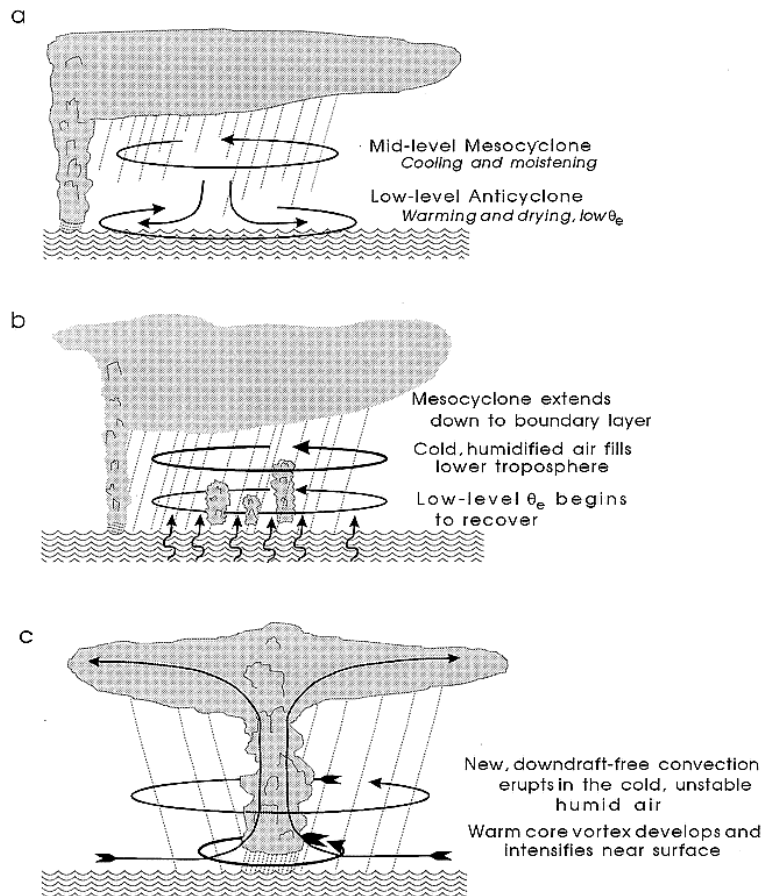


Figure 3: Conceptual model of tropical cyclogenesis from a preexisting MCS proposed by Bister and Emanuel (1997). (a) Evaporation of stratiform precipitation cools and moistens the upper part of the lower troposphere; forced subsidence leads to warming and drying of the lower part. (b) After several hours there is a cold and relatively moist anomaly in the whole lower troposphere. (c) After some recovery of the boundary layer θ_e , convection redevelops. Image taken from Fig. 13 of Bister and Emanuel (1997).

While this theory of downward vorticity advection might, at first sight, appear to contradict Haynes and McIntyre's (1987) statement that there can be no net transfer of absolute vertical vorticity across an isobaric surface, tilting of horizontal vorticity at the downdraft edges will act to oppose the local changes within the downdraft (see Tory et al. 2006b for details). If the tilting is sufficiently intense, anticyclonic absolute vertical vorticity will be generated in the vicinity of the updraft edges. For Bister and Emanuel's downward advection process to impart a net cyclonic change the anticyclonic absolute vorticity must be eliminated. One way to achieve this result is through vortex

interactions whereby anticyclonic absolute vorticity is expelled from the emerging cyclonic core (e.g., Montgomery and Enagonio 1998). This aspect was not discussed in Bister and Emanuel (1997).

We believe this process, if it does operate, will not greatly enhance the low-level cyclonic absolute vorticity, because it will be continually weakened by low-level divergence associated with the mesoscale downdraft. Unlike the Ritchie and Montgomery theories, this theory has not been pursued beyond the initial work. Although, recently the potential for a thermodynamic adjustment of the lower tropospheric state, by evaporation of rain, to favor near downdraft free convection is being reconsidered by Kerry Emanuel and colleagues (Personal Communication, K. Emanuel, 2006).

Raymond et al. (1998) investigated the mean vorticity, divergence and vertical mass flux within MCSs associated with a number of developing TC's observed during TEXMEX. They showed that often during the early stages of development the MCS kinematic structure resembled that of a system dominated by stratiform dynamics (vorticity maximised at mid-levels, mid-level convergence with divergence above and below, mean subsidence in the lower troposphere and upward motion above). As the systems intensified, the MCS kinematic nature became increasingly more convective (vorticity intensifying at lower-levels, lower tropospheric convergence, upper tropospheric divergence, mean tropospheric updrafts). They noted that the transition appeared to be coupled with an increase in the mid-level relative humidity. These kinematic observations are consistent with all three theories above. The theories differ in that the top-down theories suggest that low-level convergence becomes important after genesis is complete, whereas the bottom-up theory suggests that low-level convergence is an integral part of the genesis process.

2.2.2.2 Confusion surrounding loose genesis definition, and understanding of genesis progression

During the last decade, the debate between the two camps has been complicated by a loose definition of TC genesis, which is yet to be tied down. The top-down theories were based on the premise that at an early stage in their lifecycle MCSs typically have a MCS-scale surface anticyclone below the stratiform precipitation deck (commonly observed in mid-latitude terrestrial MCSs, e.g., Fritsch et al., 1994; Houze, 2004). Thus these theories focused on mechanisms that erode the surface anticyclone and replace it with cyclonic vorticity. In a number of earlier top-down studies (e.g., Bister and Emanuel 1997; Simpson et al. 1997; Ritchie and Holland 1997; Harr et al. 1996a,b) it has been suggested that TC genesis is the process that replaces the surface anticyclone. In these studies, the role of tropical waves in the genesis preconditioning process was recognised, as was the role of vortex enhancement in MCSs embedded in the preconditioned environment (as mentioned above). They also recognised that relatively large-scale regions of near downdraft-free convection played an important role in amplifying the TC vortex at low levels, and that low-level cyclonic vorticity must be present in the convective region before such amplification can take place. They recognised also that before near downdraft-free convection can develop the typically observed "onion-shaped" temperature and dewpoint profiles must be replaced with a moist-neutral profile. (Bister and Emanuel were not that specific. They commented only on moistening below the MCS.) Thus there appeared to be two roadblocks to TC genesis, one kinematic (low-level anticyclone) and

one thermodynamic ("onion-shaped" profile). The top-down merger theory focused on the kinematic roadblock, while the top-down showerhead theory considered both roadblocks. Whether the top-down mechanism brought sufficient cyclonic vorticity to the surface to kick-start the hurricane heat engine, or generate a warm-core TC scale vortex was not of great importance to these theories.

The Montgomery camp has suggested deep-convective, low-level vortex enhancement was taking place within MCSs well before a TC-scale vortex had formed, and well before the system-scale vortex became self-sustaining through a positive feedback between the surface winds and sea-to-air fluxes of latent and sensible heat from the underlying ocean. That is, sufficient low-level cyclonic vorticity was assumed to already be present in their MCS conceptual model, at least in the convective regions of the MCS. Thus, if there was ever any need to replace anticyclonic vorticity at the surface with cyclonic vorticity it must have occurred well before genesis took place. Their recent modeling studies (summarized below) suggest that vorticity enhancement in convective regions can proceed prior to the establishment of a moist-neutral lower-troposphere.

At this point a specific definition of genesis might have helped clarify the debate. If genesis was said to be complete once a lower-tropospheric warm-cored TC-scale vortex had formed, then the top-down proponents would likely have agreed that the genesis process must continue beyond the arrival of cyclonic vorticity to the surface and include the low-level vortex enhancement in deep convective regions (which they believed was necessary to amplify the already formed TC) to bring about the lower tropospheric, warm-core structure.

In recent modelling and observational studies discussed below there does not appear to be any evidence that surface anticyclones below MCSs hamper the genesis process. It may be that warming from ocean heat fluxes weakens the surface cold layer, which in turn reduces the low-level divergence and the potential for the development of substantial anticyclonic relative vorticity, when compared with the terrestrial midlatitude MCSs (e.g., as discussed in Fritsch et al. 1994). On the other hand, significant anticyclonic relative vorticity caused by low-level divergence, becomes less likely with proximity to the equator (assuming the MCS initially developed in a low-level cyclonic absolute vorticity environment). This is because divergence cannot change the sign of *absolute* vorticity. It can only weaken the absolute vorticity magnitude, in which case the anticyclonic *relative* vorticity magnitude can at most approach the magnitude of the planetary vorticity. Furthermore, if the dynamics change and divergence is replaced with convergence (e.g., the previously stratiform area becomes dominated by deep convection) the weak anticyclonic *relative* vorticity will become cyclonic as the cyclonic *absolute* vorticity intensifies, and the kinematic roadblock has been overcome.

These studies suggest that vorticity enhancement in deep convective regions with pre-existing cyclonic vorticity plays an important role from the very early stages of genesis, and while MCV merger can and probably does take place it would not appear to be necessary for genesis.

2.2.2.3 Bottom-up theory evolves

The continuation of the top-down versus bottom-up debate was in part due to insufficient observational evidence to suggest with sufficient

certainty that either process actually occurred in the real atmosphere. Bister and Emanuel (1997), Ritchie and Holland (1997), Simpson et al. (1997) all attempted to demonstrate their respective top-down mechanisms in observational studies, but we believe there was insufficient evidence to prove or disprove any of the theories in any of the examples. Until recently the Montgomery camp focussed on modelling to develop their theory. They began with highly idealised models in which the bottom-up theory was born, moved to high-resolution, cloud-resolving forecast models (Hendricks et al., 2004) and high-resolution cloud resolving idealized models (Montgomery et al., 2006). They found that vortical hot towers (VHT) on scales of 10–20 km played an essential role in both the realistic and idealised genesis studies. The VHT vortical structure and diabatic heating are illustrated in Fig. 4.

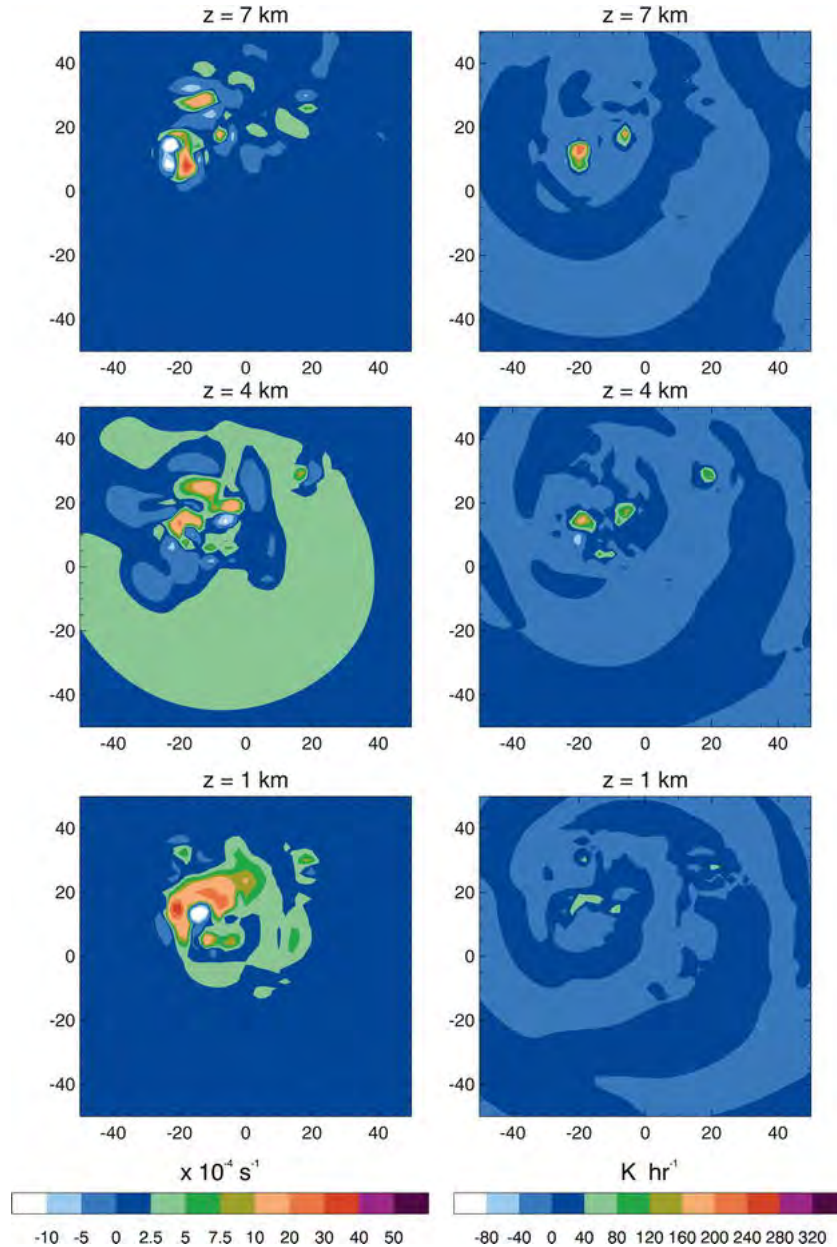


Figure 4: Absolute vorticity $f + \zeta$ in units of 10^{-4} s^{-1} (left) and diabatic heating rate $\dot{\theta}$ in units of K h^{-1} (right) on horizontal surfaces $z = 1, 4$, and 7 km at $t = 7$ h into the control simulation. Axes are in km. Image taken from Fig. 3 of Montgomery et al. (2006).

These vortices provided seed vorticity that contributed to a vortex upscale cascade, and net heating that fuelled a system scale intensification (SSI) process, both deemed essential for genesis. (An example of vortex upscale cascade taken from Hendricks et al. (2004) is presented in Fig. 5.) The SSI process enhances vorticity on the system-scale by converging pre-existing and convectively intensified cyclonic vorticity via the Eliassen circulation within a quasi-balanced vortex driven primarily by latent heating within hot tower cores. These results were greeted with skepticism. When the VHT theory was presented VHTs were largely unheard of, which made broad acceptance of the theory more improbable. Until recently observations of VHTs on this scale have been very elusive. This is not surprising given that they are likely to be obscured by the larger scale convection in which they are embedded, and their small scales makes them difficult to identify in more traditional observational networks including aircraft flight data.

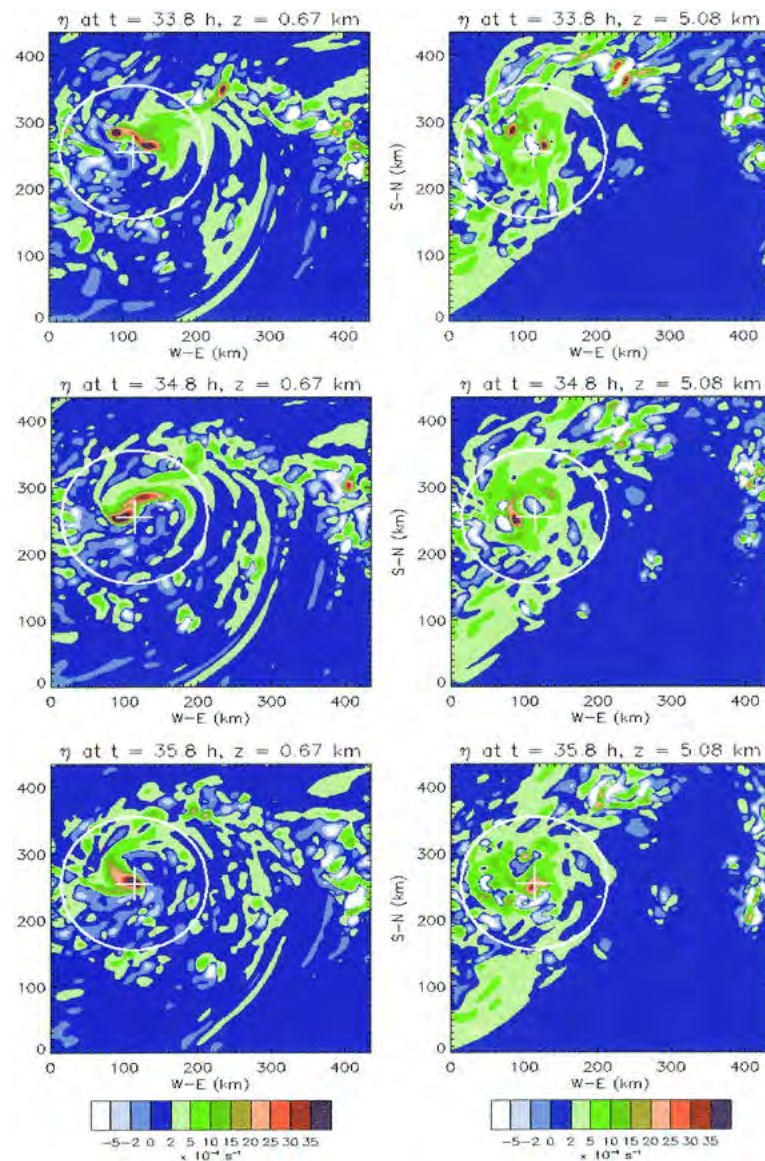


Figure 5: Plan views of absolute vertical vorticity at low (left panels) and midlevels (right panels) of the troposphere. Note the merger of the two anomalies at low-levels. Image taken from Fig. 11 of Hendricks et al. (2004).

2.2.3. Genesis definitions

The genesis definition problem is not just confined to the dynamical processes of vortex enhancement on the mesoscale. The genesis process is usually identified as a synoptic-scale pre-conditioning followed by a mesoscale organisation into a TC-scale vortex (e.g., Karyampudi and Pierce, 2002). In some articles the distinction is blurred and it is not clear whether the authors are referring to a synoptic or mesoscale vorticity enhancement process. Karyampudi and Pierce (2002) describe the synoptic scale pre-conditioning as Stage 1 of genesis (e.g., recent studies include Molinari et al. 2000; Bracken and Bosart 2000; Dickinson and Molinari 2002; Li et al. 2003), and the mesoscale generation and interaction of vorticity anomalies associated with one or more MCSs as Stage 2. We will adopt this terminology in the remainder of the report. Clearly the topic of internal influences on TC formation is associated with Stage 2 of genesis, and this will remain the focus of the report. However, it should be noted that the larger-scale environment can influence the location of the convective forcing that initiates Stage 2 (e.g., Chen et al. 2004), which could then influence the TC formation rate, intensity and track (e.g., Tory et al. 2006c).

2.2.4. Recent modelling results and observational studies

2.2.4.1 The collective effect of VHTs

The high-resolution, cloud-resolving forecast of Hurricane Diana described in Hendricks et al. (2004) was the first study to quantitatively analyse the real genesis potential of vortex enhancement by convective-scale updrafts. Their 3 km grid spacing led to minimum convective scales of approximately 12–15 km, with associated VHTs of that scale and larger. Although their sensitivity experiments with grid spacing of 1¹ km produced smaller convective scales and smaller-scaled VHTs, the basic path to genesis was unchanged. The idealized study of Montgomery et al. (2006) showed that the basic genesis mechanisms of vortex upscale cascade and SSI evident in the Hendricks et al. study of Hurricane Diana was a consistent result in high-resolution, cloud-resolving models (MM5 and RAMS, respectively). Doubts about the realism of this genesis path should then be directed toward the cloud physics, initial conditions and perhaps the model resolution.

A recent observational study of the formation of Hurricane Dolly (1996) by Reasor et al (2005) has provided evidence that the VHT path, as described in Hendricks et al. (2004) and Montgomery et al. (2006), does happen in the real world. Reasor et al. (2005) analysed Doppler radar data from the genesis of Hurricane Dolly to illustrate vortex enhancement in a MCS. Their analysis suggested mid-level vortex enhancement in the stratiform precipitation region, consistent with the mid-latitude terrestrial MCS theory, as well as low-level vortex enhancement on the convective scale consistent with the VHT theory. Sippel et al. (2006) also identified intense vortices associated with individual cumulonimbus in Doppler radar data of varying scales from 1.5–5 km. Although smaller in scale than the VHTs discussed in Hendricks et al. (2004) and Montgomery et al. (2006), these vortices exhibited similar vortex interactions during the formation of Tropical Storm Allison (2001).

¹ An additional 1 km resolution study is underway as part of Marc Hidalgo's PhD thesis, due to be finished in October, 2006.

These observational studies suggest that the minimum VHT scale is about 3–4 km in diameter. Both studies show meso- β -scale (10–100 km) vortices with meso- γ -scale (1–10 km) vortices embedded, which is suggestive of stratiform and convective-type vortex enhancement at work simultaneously. Both also show a “feeder band” of convection leading to the dominant vortex core with multiple meso- γ scale vortices embedded. This is illustrated in Fig. 6 from Reasor et al. (2005) and in Fig. 7 from Sippel et al. (2006).

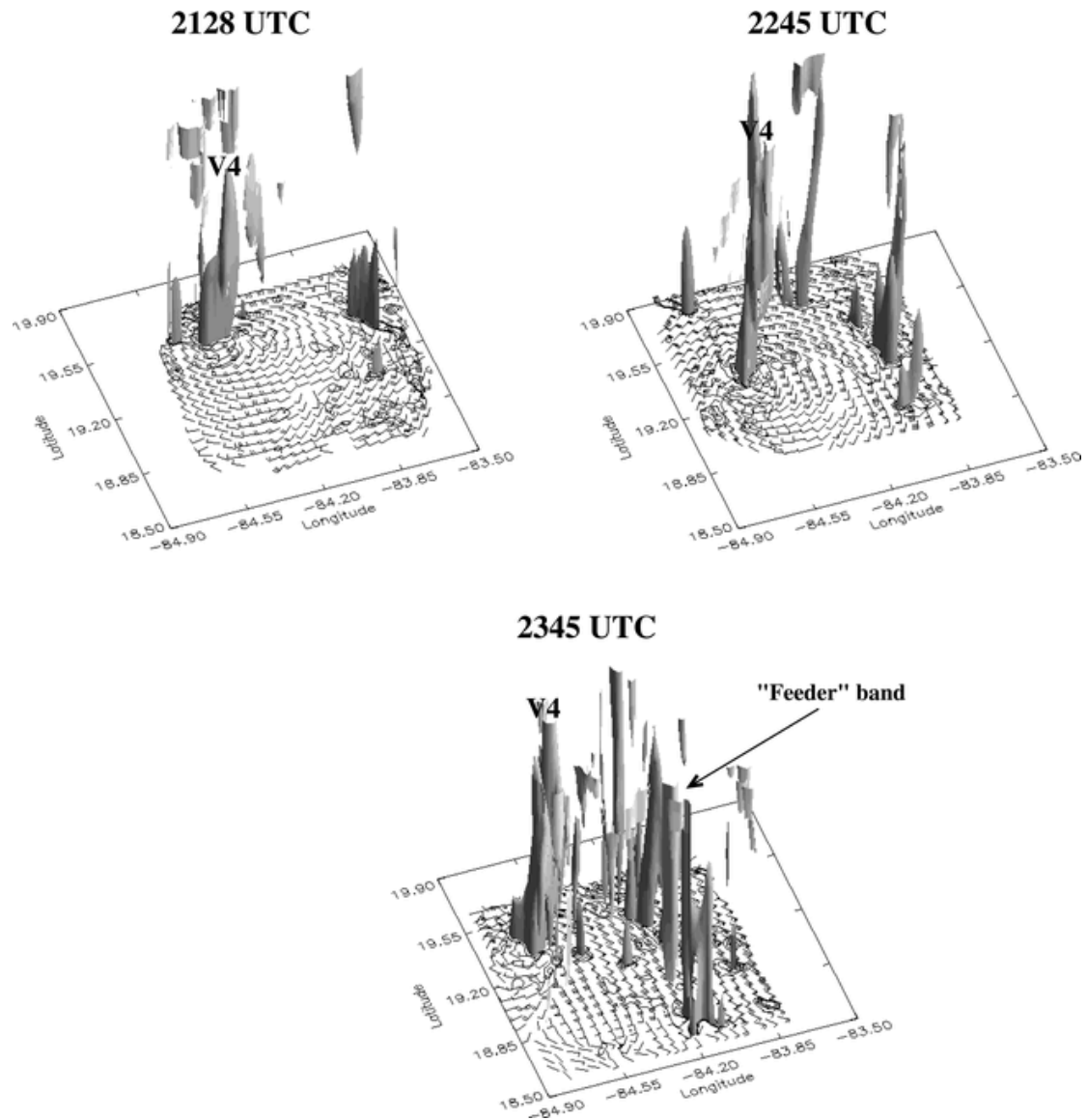


Figure 6: Three-dimensional iso-surface of the vertical component of relative vorticity ($15 \times 10^{-4} \text{ s}^{-1}$) between 1 and 7 km, and the horizontal winds at a height of 1 km, observed during the formation of Hurricane Dolly on 19 August 1996. Shown is the development of the low-level vortex at 2128, 2245, and 2345 UTC (clockwise from top). The feeder band about vortex V4 intensifies and spirals in toward the vortex core. Image taken from Fig. 12 of Reasor et al. (2005).

With time, the smaller scale vortices merged as they were fed into the vortex core. Many of these vortices were relatively shallow. Sippel et al. (2006) found the typical radii of the vortices were less than 5 km, which was twice the size of the parent convective cell. It would be

interesting to know whether a similar ratio between the convective cell size and associated vortex also applies to larger scale cells and indeed deep convective regions more generally. The vorticity estimates ranged from 10^{-3} to 10^{-2} s^{-1} , with a peak of near $1.5 \times 10^{-2} \text{ s}^{-1}$. Sippel et al. (2006) commented that these scales and intensities are comparable with tornadic mesocyclones documented by Spratt et al. (1997) in TC rainbands.

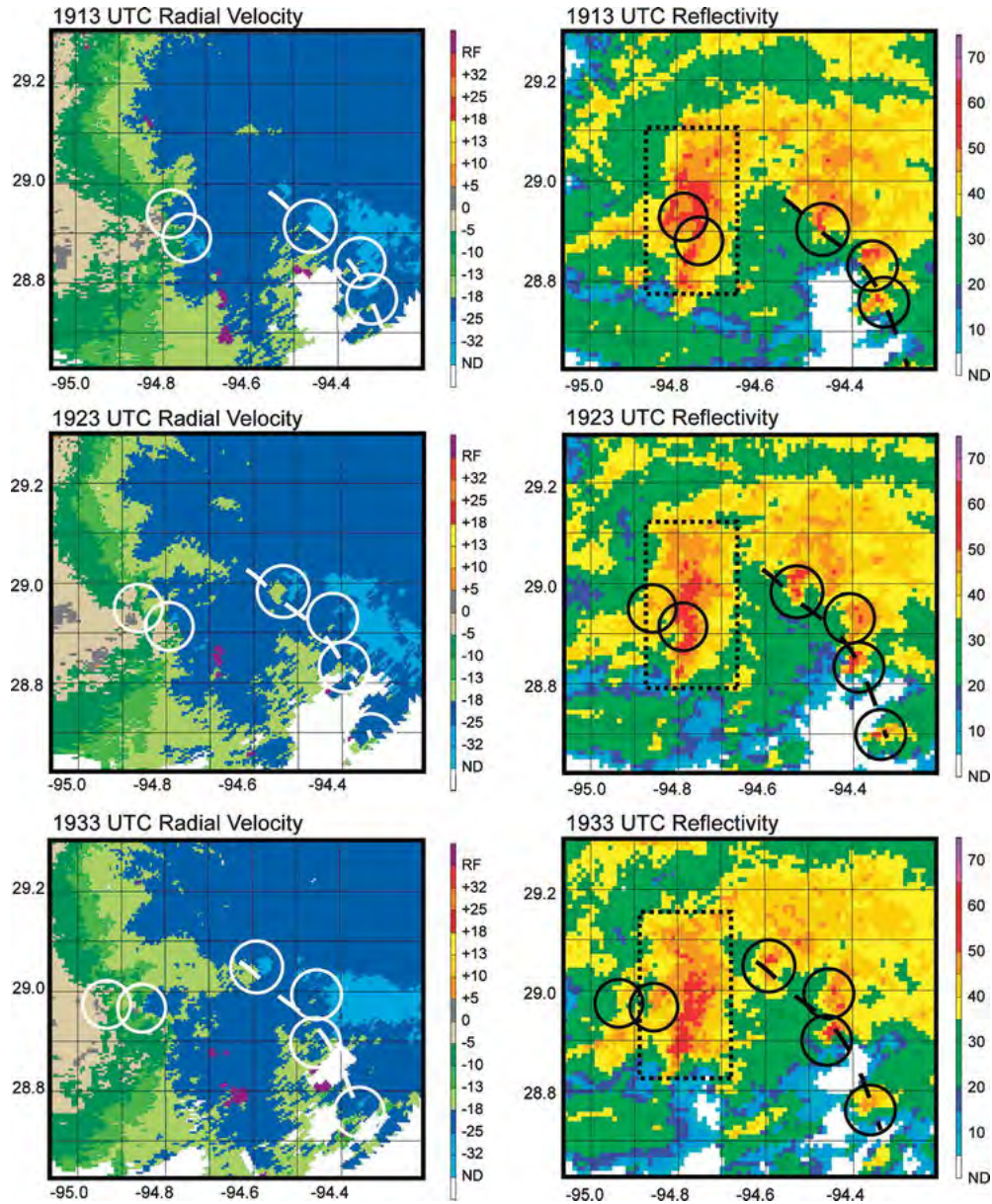


Figure 7: The 0.3° KHGX radial velocity and reflectivity images from 5 June 2001 during the formation of Tropical Storm Allison. For reference, meso- γ -scale vortices discussed in the text are located at the center of the circles. The circle radius is approximately twice the associated vortex radius of the maximum winds. The velocity scale is in m s^{-1} , and the reflectivity scale is in dBZ. A shear/rainband axis is denoted by the white (black) dashed line in velocity (reflectivity) data. The convection enclosed by the dotted line is a “central core” of convection. Image taken from Fig. 13 of Sippel et al. (2006).

Now that VHTs of similar scale to those modeled by Hendricks et al. (2004), Montgomery et al. (2006) and Davis and Bosart (2006, see below)

have been observed exhibiting similar behavior with respect to the upscale vortex cascade, the VHT route to TC genesis must be recognised as a possible route to genesis.

Davis and Bosart (2006) performed a high-resolution, cloud-resolving simulation of Hurricane Humberto (2001). They also found VHT-like activity played an important role in the genesis process, as in Hendricks et al. (2004) and Montgomery et al. (2006). Vorticity budgets showed the dominant vortex enhancement mechanism was low-level vorticity convergence in deep convective regions. They found significant condensational heating from convective updrafts drove "the transverse circulation necessary for the spin up of the azimuthal mean vortex" (SSI process). Humberto formed in a sheared environment, which favored convection in the downshear-left quadrant of the nascent cyclone.

Perhaps the most interesting feature of the Davis and Bosart (2006) simulation is the identification of the mesoscale convective behavior that led to the early construction of the low-level vorticity feature that became the cyclone core. Convection was initiated in a region of "warm-air advection" in the vicinity of a large-scale convergence line. Convection formed along this line by 12 hours into the simulation. The convective line had a similar structure to a mid-latitude terrestrial MCS squall line (e.g., recent studies include Bryan and Fritsch 2000; James et al. 2005, 2006), including strong line-perpendicular, low-level inflow and deep convection along the line with what appears to be a stratiform precipitation deck behind. Evaporative cooling is significant in the first 100 km behind the line, which contributes to low-level divergence. Perhaps because the stratiform rain-induced lower-tropospheric cooling was concentrated within 100 km of the convective line, the magnitude of this cooling was significant. A bore began to propagate away from the convective line (Mapes 1993), which resulted in lower tropospheric lifting and associated moistening and cooling (about 2 K) in the lower half of the troposphere. Within a 200 by 300 km region behind the bore (as well as the leading edge of the bore) deep convection developed with weakened downdrafts, which they attributed to the higher humidity. This convection is evident in Fig. 8a, which shows convective activity between two lines roughly oriented southwest-northeast, one in the lower-right of the panel (the squall line front) and the other near the center of the panel (leading edge of the propagating bore). The resulting mean convergence served to enhance the pre-existing cyclonic absolute vorticity and generate the low-level nascent cyclone within about 6 hours of the convective line forming. The enhanced low-level cyclonic relative vorticity is evident in Fig. 8b. Davis and Bosart (2006) suggested that an upper-level PV anomaly played an important role in this process by providing vertical wind shear that helped set up the convective line MCS dynamics.

Note this environment was neither saturated nor moist neutral, which are conditions believed to be necessary for downdraft-free convection. Davis and Bosart (2006) commented that the cooling and moistening caused by the passage of the bore led to a reduction in downdraft intensity, which improved the efficiency of cyclonic vorticity production in the boundary layer. From this study, Hendricks et al. (2004) and Montgomery et al. (2006), it would seem that downdraft free convection may not be essential for TC genesis.

Vertical wind shear also favored mesoscale regions of ascent in the developing vortex due to the dynamic response of a tilted vortex that leads to rising motion on the down-tilt side (e.g., Raymond and Jiang 1990; Raymond et al. 1998; Jones 1995). Mesoscale ascent in both the bore and on the down-tilt side of the developing TC-scale vortex led to

cooling and moistening which reduced the stability of the lower troposphere and reduced the potential for downdrafts. These conditions favor the development of convective regions with net low- to mid-level convergence.

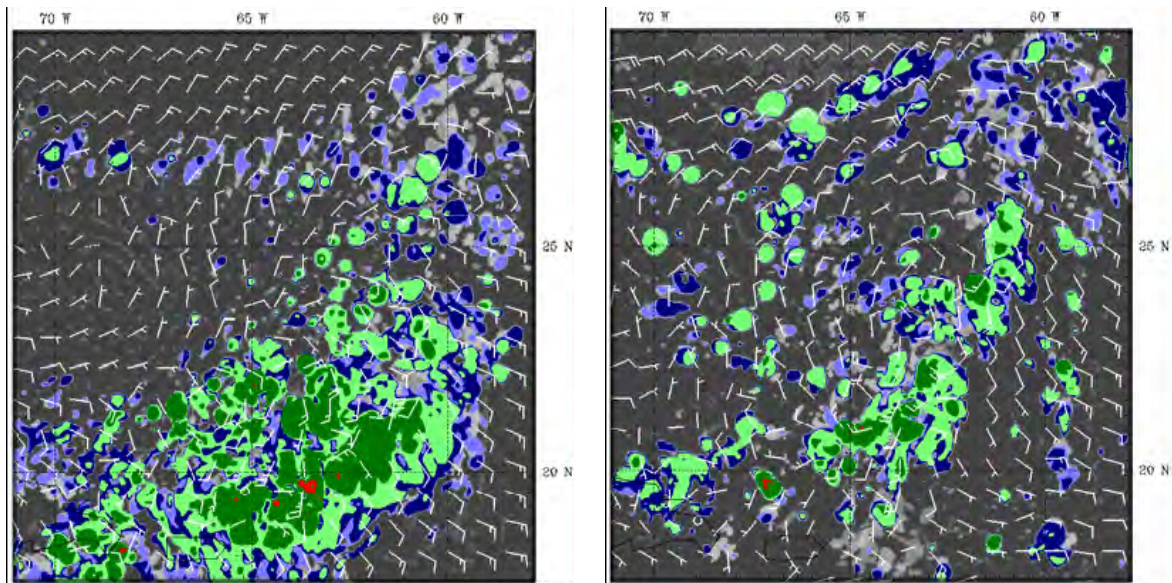


Figure 8: Model-derived cloud-top temperature and 10-m wind for (a) 15 UTC 19 Sept. (15 h forecast) and (b) 12 UTC 20 Sept. (36 h forecast), from a simulation of the genesis of Hurricane Humberto (2001). Image taken from Fig. 7 of Davis and Bosart (2006).

The propagation of a “cold” bore behind an MCS squall-line with its associated convection is another example of how MCS dynamics can lead to the generation of a relatively large-scale convective area. Of note is that this development occurred quite early in the Stage 2 genesis process, and that the large-scale convective area developed only about 6 hours after the initial convective line appeared. This time delay has positive implications for coarse-resolution NWP models that favor net deep convection as soon as convection is initiated (i.e., they do not resolve the finer-scale processes that lead to the ultimate convective region). If it only takes six hours for the convective region to develop, then the coarse-resolution NWP models may not be accelerating the genesis process at too great a rate. On the other hand, if the development of the convective region is sensitive to its environment as Davis and Bosart (2006) suggest, and the coarse-resolution models are not representing critical thermodynamic and kinematic processes, then false alarms may be expected. This is discussed further in the next subsection.

Davis and Bosart (2006) comment that baroclinicity (isentropic uplift) played a role in the formation of Humberto by producing a favorable region for convection, but they believe the vertical wind shear was critically important for maintaining the convection sufficiently for genesis to be successful. They hypothesized the shear acted in two ways to enhance convection. It enabled the squall line to develop (in their sensitivity experiment with weakened shear the bore that provided the moistened lower troposphere failed to develop). Shear also tilted the developing TC scale vortex, which led to mesoscale ascent on the down-tilt side. This ascent also served to moisten and cool the lower troposphere, which they suggested reduced the intensity of downdrafts. Thus, they postulate that in the deep tropics where the baroclinicity is

likely to be very weak, shear could play an important convection-maintenance role in TC genesis.

2.2.4.2 GLAPS

Tory et al. (2006a,b,c) have documented in detail the TC genesis process in an operational forecast model. The model has been developed from the Australian Bureau of Meteorology LAPS NWP model specifically with TC genesis in mind, and thus has recently been termed GLAPS (Genesis-LAPS). The model grid spacing is 0.15° lat/long. At this resolution, convective parameterization is required. Despite the relatively coarse resolution compared with Hendricks et al. (2004), Montgomery et al. (2006), and Davis and Bosart (2006), and the use of convective parameterization instead of explicit convection, the route to genesis is surprisingly similar. Convective updraft regions of 60 km diameter and greater enhance low- to mid-level vorticity mostly through vorticity convergence, driven by the net warming by latent heating in VHT cores. The individual vortex cores that develop in the convective updraft regions interact similar to observed MCSs as they are advected around the monsoon circulation in which they are embedded (i.e., a larger scale vortex upscale cascade). An example of this behaviour taken from Tory et al. (2006b) is illustrated in Fig. 9. The PV anomaly labelled A is associated with an old convective burst undergoing decay, while B is associated with a young developing convective burst. A is a stronger PV anomaly, but as Fig. 9b shows anomaly B is intensifying rapidly, while the two anomalies rotate about each other and the monsoon low they are embedded in. Fig. 9c shows B is now considerably more intense, and A has weakened and is being drawn into B. Two hours later Fig. 9d shows that B has all but consumed A, and another anomaly C has begun to develop. With time the process is repeated with C taking over as the dominant anomaly, which then consumes B after the convective burst responsible for B decays.

To help describe these processes, Tory et al. (2006a) defined primary and secondary vortex enhancement mechanisms, in which the vortex enhancement in individual updrafts (through vorticity convergence and vertical advection²) is the primary mechanism, and the vortex upscale cascade and SSI processes are secondary mechanisms.

It could be argued that convection on scales resolved by GLAPS is unrealistic. However, convective regions of such scale and larger are often observed in the pre-Stage 2-genesis environment (e.g., Harr et al 1996a,b; Ritchie and Holland 1997; Simpson et al. 1997; Ritchie 2003; Ritchie et al. 2003). This is the scale of Sippel et al. (2006) meso- β vortices, or convective burst vortices (CBV). If we accept that convective regions do exist of this scale we then ask, does the modelled vortex structure resemble observed MCS features? It has been argued for some time that these structures should be viewed as largely stratiform with an accompanying MCV, in which case there would be minimal low-level cyclonic vorticity. Large areas of very cold cloud top temperatures suggestive of nearly contiguous deep convection on scales of 100 km are often observed (Zehr 1992) during the late pre-Stage 2-genesis development, with evidence of enhanced low-level vorticity. In such environments, a deep vortex core structure is more likely to accompany the cloud mass, as was present in the Davis and Bosart (2006) simulation, than a traditional continental MCV structure.

² The net effect of vertical advection of cyclonic vorticity is offset by the net tilting which produces anticyclonic vorticity of equal magnitude on the edge of the updrafts. In this way Haynes and McIntyre's (1987) theory is not violated (Tory et al. 2006b).

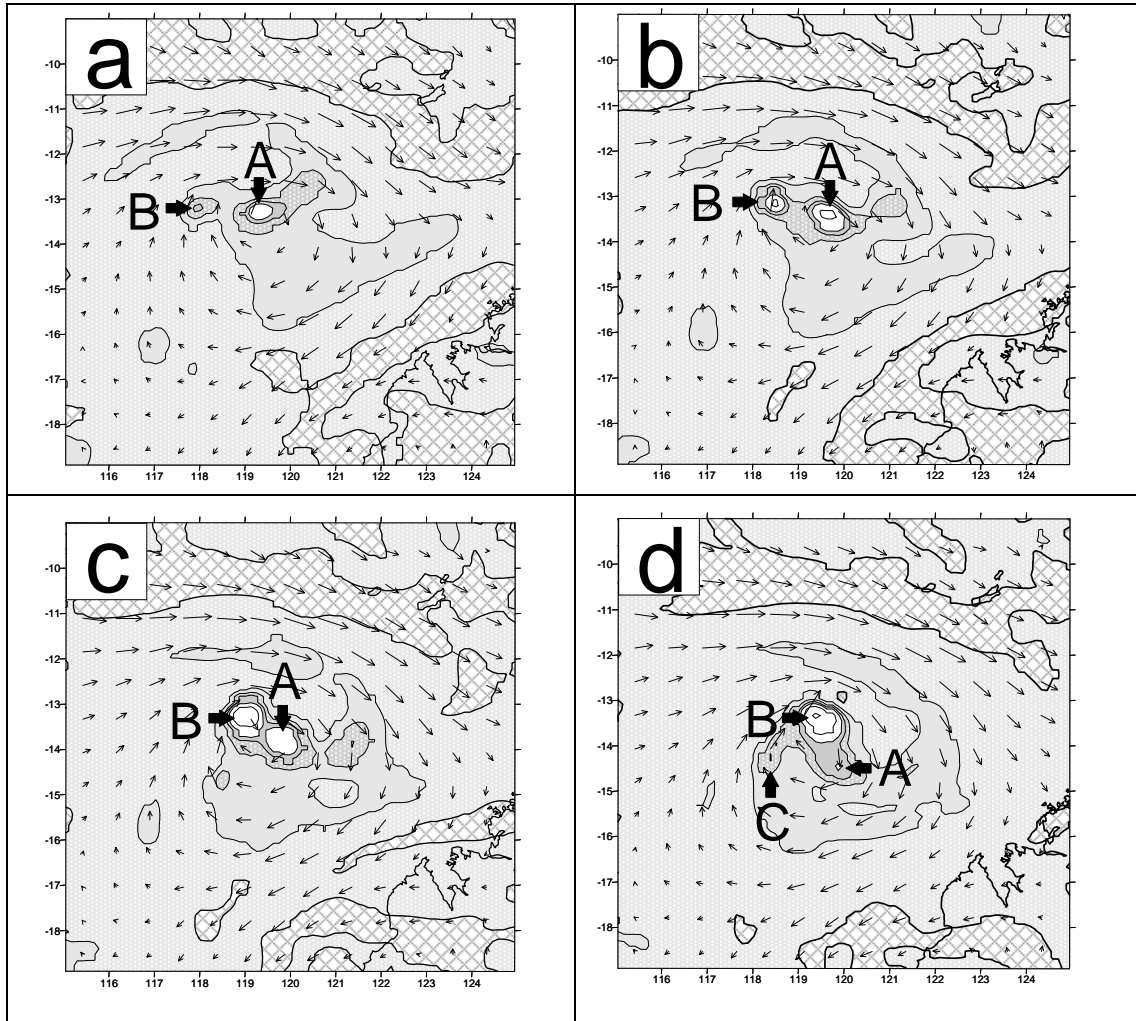


Figure 9: Potential Vorticity (PV, contour interval 0.5 PV units, anticyclonic hatched) on the 850 hPa surface from a G-LAPS simulation of TC Chris (2002). Vectors represent the horizontal winds on the 850 hPa surface. PV anomalies labelled A, B and C are associated with relatively short-lived convective bursts. PV anomalies outlive the convective bursts. Each frame is two hours apart. Image taken from Fig. 5 of Tory et al. (2006b).

This argument is supported by observations of relatively large areas of mean low- to mid-level convergence (Zipser and Gautier1978; Mapes and Houze 1992, 1995) in a number of tropical MCSs. Additionally, observations of very low cloud-top temperatures, interpreted as overshooting deep convective cloud, on the same spatial scales and larger as the TC-LAPS updrafts are frequently observed during TC genesis (Zehr 1992; Gray 1998). However, a vortex core will only develop in this environment if it is embedded in a sufficiently cyclonic environment.

Another feature often observed accompanying these large convective regions are low-level wind surges (e.g., Zehr 1992; Gray 1998). Gray has suggested that the wind surges may lead the development of the large convective blow-ups, i.e., the convergence leading the surge triggers the relatively large area of convection. Wind-surge like behavior is evident in some of the GLAPS simulations presented in Tory et al. (2006b,c), but the dynamics of the surges were not investigated. It is not clear

whether the surge leads the convection or the convection leads the surge. Ritchie et al. (2003) comment on such a surge during the development of Hurricane Floyd. The temporal resolution of their observations however was not sufficient to suggest a cause and effect relationship between the surge and updraft.

The high-resolution cloud representing simulations of Hendricks et al. (2004), Montgomery et al. (2006) and Davis and Bosart (2006) are consistent with the earlier theoretical work of Montgomery and Enagonio (1998) in that the VHTs do with time interact with the vortex in which they are embedded to form a PV monolith structure similar to the GLAPS vortex core. This behavior is partially captured in the observations presented in Reasor et al. (2005). It could be argued that GLAPS forces the immediate construction of a vortex core in convective regions, rather than allowing the more gradual building process evident in the higher resolution models of Hendricks et al. (2004), Montgomery et al. (2006) and Davis and Bosart (2006). Tory et al. argue that although it is a shortcoming of the GLAPS model, it is likely to only be significant during the early Stage 2 genesis, because later observed MCS convection and low-level convergence regions are often not too dissimilar in areal extent. Furthermore, Davis and Bosart (2006) have shown that in certain situations the development of relatively large convective areas can occur in about six hours after the initial convection appears. The SSI process plays a significant role in GLAPS TC genesis also. It is likely to play a greater role in proportionate sense to the higher resolution models if, as suggested above, the finer scale of the vortex upscale cascade has been bypassed.

Despite the GLAPS shortcomings identified above, the system reproduces many realistic aspects of genesis and Tory et al. (2006c) claim it has considerable success in forecasting both genesis and non-development, although an objective test of GLAPS performance is yet to be completed. The GLAPS simulations show convection typically develops about 200 km from the large-scale cyclonic circulation center, and with time as the system intensifies the convective regions and the associated vortex cores spiral inward. This process was often observed by Zehr (1992) and evidence exists of such behavior in satellite imagery provided in Harr et al. (1996b), Ritchie and Holland (1997), Simpson et al. (1997), Ritchie (2003), and Ritchie et al. (2003).

Perhaps the most important finding of Tory et al. (2006c) is that TC genesis is qualitatively predictable in conventional NWP forecast models (although GLAPS is not entirely conventional in its initialization, see below), which is contrary to claims that TC genesis will forever be a largely unpredictable process (e.g., Davis and Bosart 2002). Davis and Bosart (2002) based this comment on their experience with sensitivity experiments on a particular hurricane forecast, and the comment referred to intensity and track forecasts in addition to genesis. Their expectations are likely to be more quantitative than Tory et al., who only consider the simulated genesis of a TC within a few hundred km and within about 12 hours of that observed to be a success.

Tory et al. believe that qualitative TC genesis forecasting is predictable because the genesis process appears to be driven by large-scale dynamics. Provided the initialization is able to capture the large-scale environment, the model should be able to capture the genesis process, because the large-scale environment satisfies Gray's necessary genesis conditions and it contains the dynamical forcing that initiates convection. If the coarser resolution models such as GLAPS adequately capture the net effect of the unresolved vortex interactions then these

coarser resolution models should also have qualitative success in genesis forecasting.

A critical component to GLAPS is the initialization, which implants artificial heat sources in locations where very low cloud-top temperatures are observed. This ensures convection is active at the initial time in the correct location, and does not rely on the model to determine where convection first appears. Davis and Bosart (2002) commented that for the most accurate forecast various physical parameterizations would need to be tuned, and that such tuning is not likely to be consistent from event to event. In GLAPS, the arbitrary heat sources have been tuned to this effect, but broad success has been achieved by tuning to a number of borderline TC genesis cases, rather than just one case. Tory et al. (2006c) agree with Davis and Bosart that the finer detail of the evolution can be quite sensitive to initial conditions, but overwhelmingly they found that the final result in terms of vortex size, intensity and location, differed very little. This result led Tory et al. (2006c) to hypothesize that on a qualitative level the finer details of vortex numbers and sizes, and the details of vortex interactions were relatively unimportant to the overall genesis result. Instead, what was important was the state of the larger scale environment in which the system develops and the net convection that took place. They base this on the apparent importance of the SSI process, which is essentially a function of the large-scale cyclonic environment and the net heating of all convective elements.

2.2.5. Some implications of these results

Forecasters in the Australian region (and perhaps in other areas of the world) regularly use global NWP models for TC genesis guidance. The relatively coarse resolution of these models supports the argument above that genesis is on the whole predictable and that it is driven by large-scale processes. This conclusion was also reached by Camargo and Sobel (2004) in their study of TC genesis in low-resolution atmospheric GCM. Australian forecasters use ECMWF global forecasts (Jeff Callaghan, personal communication, 2006). As a rule of thumb, once a single closed isobar has formed they consider genesis to be complete. Furthermore, methods for determining tropical cyclone-like structures in NOGAPS have been developed, not so much based on recognized TC structure but on the structures present in the global model when TCs are observed (Cheung and Elsberry 2002). It could be argued that at such coarse resolution (in which the finer details cannot be resolved) the models must be getting the right answer for the wrong reason. But if they consistently get the right answer for this supposedly "wrong" reason then we must question the importance of the finer detail of TC formation. The pioneering work of Kurihara and Tuleya (1981) showed that coarse resolution (0.625° lat/long grid spacing) NWP models are capable of simulating the development of a realistic tropical storm. They commented that the warm core resulted from excess heating produced by the diabatic heating- adiabatic cooling imbalance, which essentially describes the SSI process. At such resolution, there was little evidence of a vortex upscale cascade, although an elongated vorticity anomaly became increasingly symmetric as it formed the core of the TS, and a remote anomaly appeared to orbit and be sheared by the TS vortex. In this coarse resolution case, the dominant vortex enhancement mechanisms (using Tory et al.'s terms) are the primary mechanism of vortex stretching in the updraft regions, and the secondary mechanism of SSI. The role of the vortex upscale cascade would be to simply focus the widely distributed anomalous cyclonic vorticity into a central core while expelling anomalous anticyclonic vorticity (Montgomery et al. 2006; Tory et al. 2006a,b). It is

conceivable that if the net vorticity and net heating between two simulations, in which one has high resolution and captures the intricate detail of vortex upscale cascade, and one has low resolution in which the vortex upscale cascade is reduced to the simple axisymmetrization of large-scale anomalies within the central vortex, then the resulting systems could have very similar intensity. In the same comparison, the importance of capturing the details of the vortex upscale cascade is likely to be much greater for accurate forecasts of genesis and intensification rates, and track accuracy.

2.2.6. Conclusions

To be consistent with the theory of Haynes and McIntyre (1987), which states that there can be no net transfer of absolute vorticity (PV) across a pressure (isentropic) surface, TC genesis must consist of a series of processes that cause a near-horizontal redistribution of absolute vorticity into an upright vorticity (PV) monolith. The process begins with the large-scale redistribution of absolute vorticity into cyclonic and anticyclonic circulations by tropical waves. The cyclonic components may often be amplified by convergence within the developing wave field. This large-scale vorticity redistribution, which can be considered Stage 1 of genesis, provides dynamical pre-conditioning for Stage 2. Stage 2 of genesis is driven by MCSs. The thermodynamic conditions necessary for Stage 2 genesis are nearly always met in the summertime, tropical oceanic environment where genesis is common, and for that reason the study of Stage 2 TC genesis has focussed mostly on the dynamics of vortex enhancement in MCSs. These MCSs may develop within the pre-conditioned environment where weak baroclinicity favors convection (mesoscale ascent along sloping isentropic surfaces). We suggest that the processes that favor convection are resolvable in coarse resolution NWP models.

Contemporary global NWP models (e.g. ECMWF medium-range forecast model) have some success representing TC genesis. Although these models cannot reproduce the finer details of the vortex upscale cascade, the SSI process is represented. The relative importance of the SSI and vortex upscale cascade processes in constructing the TC-scale vortex monolith is not known, but the level of success of the global NWP models suggests the SSI process is important.

The modeled convective regions consist of net low- to mid-tropospheric convergence, which enhances the low- to mid-tropospheric vorticity, and ultimately leads to the formation of a TC-scale vortex monolith. The process by which this occurs is complex and varied, but ultimately follows the same basic rules. Deep convective regions converge low-to mid-tropospheric absolute vorticity on the updraft scale and advect absolute vorticity upwards, which deepens the vortex cores (the primary enhancement mechanism). Anticyclonic vorticity forms on the edge of these updrafts, consistent with the constraints of Haynes and McIntyre (1987). The cyclonic cores interact to form larger cores and to expel anticyclonic vorticity (the vortex upscale cascade). The diabatic heating slightly outweighs the adiabatic cooling in these cores, and the net effect of multiple warm vortex cores is the amplification of the system scale secondary circulation (the SSI mechanism).

The modeling and observational results presented above on the whole contradict the top-down theories, which focused on mechanisms to bring mid-level cyclonic vorticity down to the surface. While it is recognised that convergence into stratiform precipitation regions can generate significant mid-tropospheric vortices and that merger of such vortices can lead to larger and deeper vortices, the modeling studies suggest it

is the deep convective vortex enhancement mechanisms that are responsible for the development of a warm-cored, TC-scale vortex. It would seem likely that mid-tropospheric vortex enhancement in the stratiform precipitation region, and merger of these vortices is likely to increase the probability of genesis, by enhancing the MCS cyclonic environment.

2.2.6.1 Some remaining questions about the physics of TC formation

The following questions address the uncertainty that surrounds the thermodynamic roadblock mentioned in Section 2.2.2.2. How does the MCS environment become transformed from the "onion-shaped" temperature and dewpoint profiles, to a moist neutral profile? (The assumption here is that the deep convective dynamics known to be essential for enhancing the low-level vorticity during TC formation cannot proceed until we have downdraft-free convection on the MCS-scale.) The VHT route to genesis suggests that vortex enhancement *can* proceed without this adjustment to the thermodynamic profile on the MCS scale. This result motivates the following questions:

Is downdraft-free convection on the MCS scale essential for TC genesis? Could the VHT activity generate a moist neutral lower troposphere necessary for downdraft-free convection on the MCS scale?

What conditions are necessary for VHT generation, and what processes lead to the formation of such conditions?

In order to enhance the lower-tropospheric vorticity on the MCS scale, how far can we deviate from moist neutrality and downdraft-free convection?

Are convective regions that have diameters of 100 km, observed by Zehr (1992) and others in TC genesis environments, made up of downdraft-free convection? What processes lead to the formation of these conditions on such scales?

What processes lead to the formation of these conditions on such scales?

If downdraft-free convection is necessary for TC genesis on the MCS scale, and if a moist neutral lower troposphere is necessary for downdraft-free convection, how can development proceed in a weak to moderate sheared environment, in which dry air is entrained into the MCS from outside?

2.2.7 Recommendations

1. Establish a widely accepted genesis definition. Suggestion: Treat genesis as a two-step process that concludes with the establishment of a warm-cored TC-like vortex. Consider the establishment of sub-synoptic environment favorable for genesis to be Stage 1. Consider the mesoscale organisation of this environment into the warm-cored TC-like vortex to be Stage 2.
2. Continue investigating the thermodynamic evolution of MCSs in the tropical oceanic environment.
3. Continue investigating the nature of vorticity enhancement in MCSs that develop in the genesis environment.
4. Determine why most tropical disturbances fail to become warm-cored, surface- concentrated vortices.

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Bibliography

- Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modeling study. *Mon. Wea. Rev.*, **125**, 2662–2682.
- Bracken, W. E. and L. F. Bosart. 2000: The role of synoptic-scale flow during Tropical Cyclogenesis over the North Atlantic Ocean. *Mon. Wea. Rev.*, **128**, 353–376.
- Bryan, G. H., and M. J. Fritsch. 2000: Moist absolute instability: The sixth static stability state. *Bull. Amer. Met. Soc.*, **81**, 1207–1230.
- Camargo, S. J. and A. H. Sobel, 2004. Formation of tropical storms in an atmospheric general circulation model, *Tellus*: **56A**, 56–67.
- Chen, Tsing-Chang, S.-Y. Wang, M.-C. Yen and W. A. Gallus Jr.. 2004: Role of the monsoon gyre in the interannual variation of Tropical Cyclone formation over the Western North Pacific. *Weather and Forecasting*, **19**, 776–785.
- Cheung, K. K. W., and R. L. Elsberry, 2002: Tropical cyclone formations over the western north Pacific in the Navy operational global atmospheric prediction system forecasts. *Weather and Forecasting*. **17**, 800–820.
- Davis, C., and L. F. Bosart, 2002: Numerical simulations of the genesis of hurricane Diana (1984). Part II: Sensitivity of track and intensity prediction. *Mon. Wea. Rev.*, **130**, 1100–1124.
- Davis, C. A. and L. F. Bosart, 2006: The formation of Hurricane Humberto (2001): The importance of extra-tropical precursors. *Quart. J. Roy. Meteor. Soc.* (coming soon).
- Dickinson, M.J., and J. Molinari, 2002: Mixed Rossby-gravity waves and western Pacific tropical cyclogenesis. Part I: Synoptic evolution. *J. Atmos. Sci.*, **59**, 2183–2196.
- Dritschel, D. G., and D. W. Waugh, 1992: Quantification of the inelastic interaction of unequal vortices in two-dimensional vortex dynamics. *Phys. Fluids A*, **4**, 1737.
- Enagonio, J. and M. T. Montgomery, 2001: Tropical cyclogenesis via convectively forced vortex Rossby waves in a shallow water primitive equation model. *J. Atmos. Sci.*, **58**, 685–706.
- Fritsch, J. M., J. D. Murphy and J. S. Kain, 1994: Warm core vortex amplification over land. *J. Atmos. Sci.*, **51**, 1780–1807.
- Gray, W. M., 1998: The formation of Tropical Cyclones. *Meteor. Atmos. Phys.* **67**, 37–69.

- Harr, P. A., M. S. Kalafsky and R. L. Elsberry, 1996a: Environmental conditions prior to formation of a midget tropical cyclone during TCM-93. *Mon. Wea. Rev.* **124**, 1693–1710.
- Harr, P. A., R. L. Elsberry and J. C. L. Chan, 1996b: Transformation of a large monsoon depression to a tropical storm during TCM-93. *Mon. Wea. Rev.* **124**, 2625–2643.
- Haynes, P. H. and M. E. McIntyre, 1987: On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces. *J. Atmos. Sci.*, **44**, 828–841.
- Hendricks, Eric A., M. T. Montgomery and C. A. Davis. 2004: The Role of "Vortical" Hot Towers in the Formation of Tropical Cyclone Diana (1984). *J. Atmos. Sci.*, **61**, 1209–1232.
- Houze, R. A., 2004: Mesoscale Convective Systems. *Reviews of Geophysics*, **42**, RG4003, 1–43.
- James, R. P., J. M. Fritsch and P. M. Markowski. 2005: Environmental Distinctions between Cellular and Slabular Convective Lines. *Mon. Wea. Rev.*, **133**, 2669–2691.
- James R. P., P. M. Markowski and J. M. Fritsch. 2006: Bow Echo Sensitivity to Ambient Moisture and Cold Pool Strength. *Mon. Wea. Rev.*, **134**, 950–964.
- Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc.*, **121**, 821–851.
- Karyampudi, V. M., and H. F. Pierce, 2002: Synoptic-scale influence of the Saharan air layer on tropical cyclogenesis over the eastern Atlantic. *Mon. Wea. Rev.*, **130**, 3100–3128.
- Kurihara, Y., and R. E. Tuleya, 1981: A numerical simulation study on the genesis of a tropical storm. *Mon. Wea. Rev.*, **109**, 1629–1653.
- Li, T., B. Fu, X. Ge, B. Wang, and M. Peng. 2003: Satellite data analysis and numerical simulation of tropical cyclone formation, *Geophys. Res. Lett.* **30**, 2122.
- Mapes, B. E. and R. A. Houze, 1992: An integrated view of the 1987 Australian monsoon and its mesoscale convective systems. I: Horizontal structure. *Quart. J. Roy. Meteor. Soc.*, **118**, 927–963.
- Mapes, B. E., 1993: Gregarious tropical convection, *J. Atmos. Sci.*, **50**, 2026–2037.
- Mapes, B. E. and R. A. Houze, 1995: Diabatic divergent profiles in Western Pacific Mesoscale Convective Systems. *J. Atmos. Sci.*, **52**, 1807–1828.
- Molinari, J. D. Vollaro, S. Skubis and M. Dickinson. 2000: Origins and mechanisms of Eastern Pacific Tropical Cyclogenesis: A case study. *Mon. Wea. Rev.*, **128**, 125–139.
- Montgomery, M. T. and J. Enagonio, 1998: Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model. *J. Atmos. Sci.*, **55**, 3176–3207.

- Montgomery, M. T., M. E. Nicholls, T. A. Cram and A. Saunders, 2006: A "vortical" hot tower route to tropical cyclogenesis. *J. Atmos. Sci.*, **63**, 355–386.
- Raymond, D. J., C. L'opez-Carillo, and L. L'opez-Cavazos, 1998: Case-studies of developing east Pacific easterly waves. *Quart. J. Roy. Meteor. Soc.*, **124**, 2005–2034.
- Raymond, D. J. and H. Jiang, 1990: A theory for long-lived convective systems, *J. Atmos. Sci.*, **47**, 3067–3077.
- Reasor, P. D., M. T. Montgomery and L. F. Bosart. 2005: Mesoscale observations of the genesis of Hurricane Dolly (1996). *J. Atmos. Sci.*, **62**, 3151–3171.
- Ritchie, E. A. and G. J. Holland, 1997: Scale interactions during the formation of Typhoon Irving. *Mon. Wea. Rev.*, **125**, 1377–1396.
- Ritchie, E. A., J. Simpson, W. T. Liu, J. Halverson, C. S. Velden, K. F. Brueske and H. Pierce, 2003: Present day satellite Technology for hurricane research. Chapter 12, *Hurricane: Coping with disaster*. Ed. R. Simpson, American Geophysical Union, 360 pp.
- Ritchie, E. A., 2003: Some aspects of mid-level vortex interaction in tropical cyclogenesis. Chapter 12, *Cloud systems, hurricanes and the Tropical Rainfall Measuring Mission (TRMM): A tribute to Dr. Joanne Simpson*. Ed. W-K Tau and R. Adler. American Meteorological Society.
- Simpson, J., E. A. Ritchie, G. J. Holland, J. Halverson and S. Stewart, 1997: Mesoscale interactions in Tropical Cyclone Genesis. *Mon. Wea. Rev.*, **125**, 2643–2661.
- Sippel, J.A., J. W. Nielsen-Gammon and S. E. Allen. 2006: The Multiple-Vortex Nature of Tropical Cyclogenesis. *Mon. Wea. Rev.*, **134**, 1796–1814.
- Spratt, S. M., D. W. Sharp, P. Welsh, A. Sandrik, F. Alsheimer and C. Paxton. 1997: A WSR-88D assessment of Tropical Cyclone outer rainband tornadoes. *Weather and Forecasting*, **12**, 479–501.
- Tory, K. J., M. T. Montgomery and N. E. Davidson, 2006a: Prediction and diagnosis of Tropical Cyclone formation in an NWP system. Part I: The critical role of vortex enhancement in deep convection. *J. Atmos. Sci.* (Accepted.)
- Tory, K. J., M. T. Montgomery, N. E. Davidson and J. D. Kepert, 2006b: Prediction and diagnosis of Tropical Cyclone formation in an NWP system. Part II: A detailed diagnosis of tropical cyclone Chris formation. *J. Atmos. Sci.* (Accepted.)
- Tory, K. J., M. T. Montgomery and N. E. Davidson, 2006c: Prediction and diagnosis of Tropical Cyclone formation in an NWP system. Part III: Developing and non-developing storms. Submitted to *J. Atmos. Sci.*
- Zehr, R., 1992: Tropical cyclogenesis in the western North Pacific. NOAA Tech. Rep. NESDIS 61, 181 pp.
- Zipser, E. J. and C. Gautier, 1978: Mesoscale events within a GATE tropical depression. *Mon. Wea. Rev.*, **106**, 789–805.